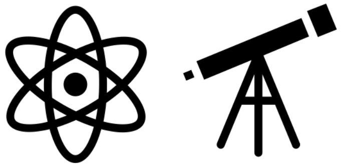
Radio Detection of Neutrinos in Ice, and Detectors in Ice

Brian Clark

Michigan State University

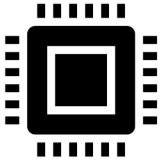
Snowmass Community Summer Study
Seattle, WA
July 19th, 2022

Bottom Line Up Front (outline)



Studying UHE (>10 PeV) neutrinos is motivated by particle physics and astrophysics

The radio technique offers an efficient way to achieve necessary effective volumes (>100 km^3)



The technology is mature, and supported by >decade of development and heritage

<u>We are ready for a large-scale experimental effort</u>

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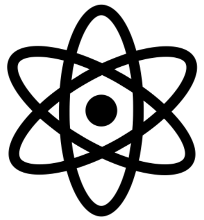
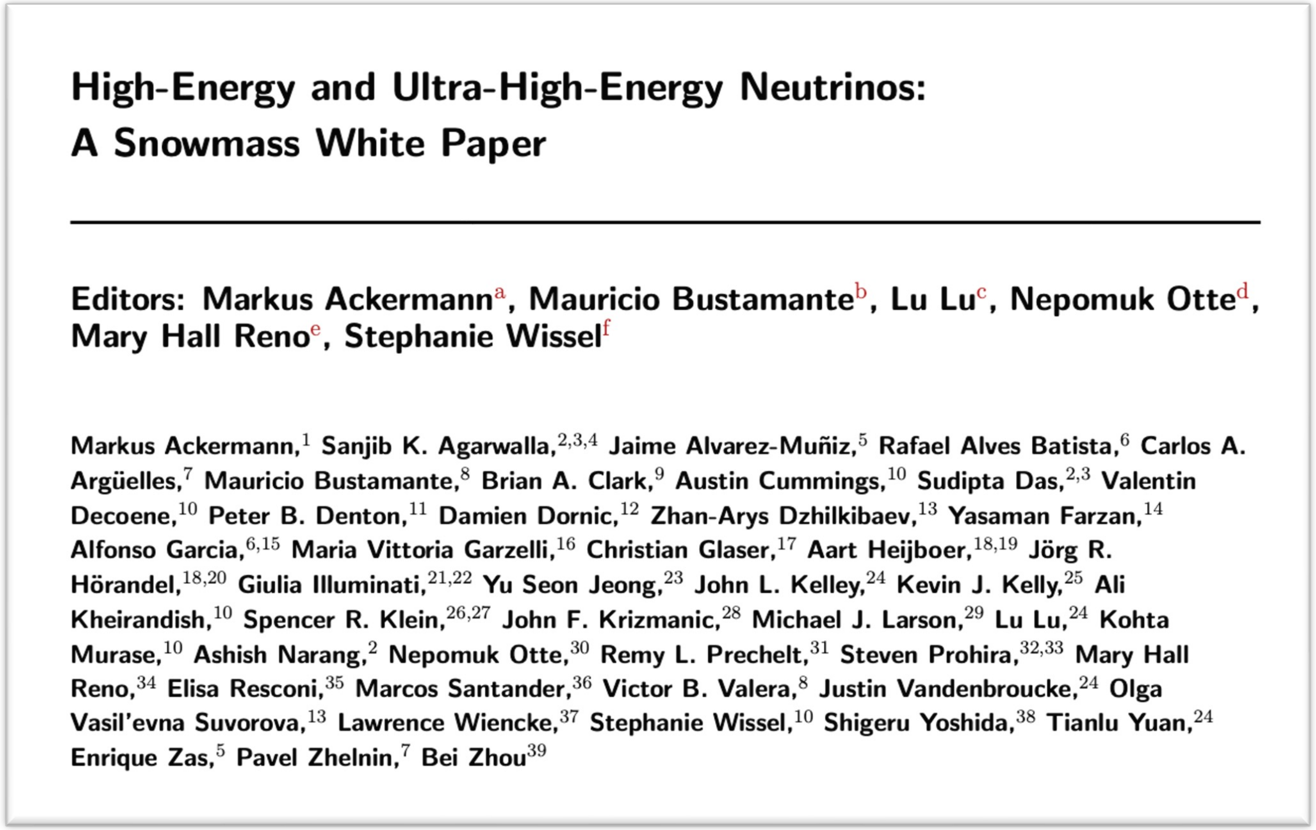
Why Study UHE (>10 PeV) Neutrinos?

A Diverse Science Case



Particle Physics

Astrophysics



High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

Editors: Markus Ackermann[a], Mauricio Bustamante[b], Lu Lu[c], Nepomuk Otte[d], Mary Hall Reno[e], Stephanie Wissel[f]

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arXiv 2203.08096

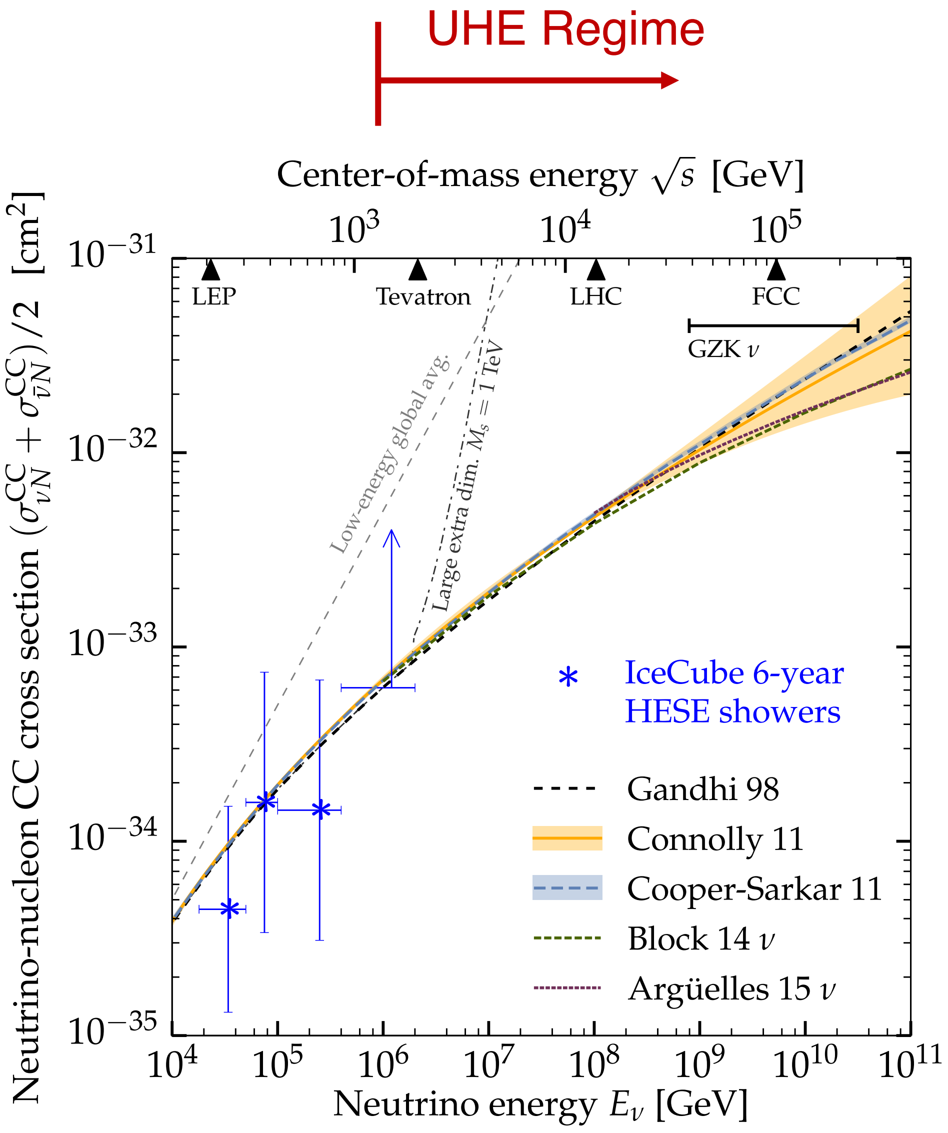
See also CF7: “Cosmic Probes of Fundamental Physics”

Particle Physics

>TeV neutrinos are the highest energy leptons ever observed

Unique portals to particle physics at high energies

- $\nu - N$ cross-section, inelasticity beyond accelerators ($\sqrt{s}\sim 30$ TeV)
- Flavor oscillations at high-E and long baselines (Gpc)
- Fundamental properties: Lorentz Invariance, secret/self-interactions, DM annihilation ($\chi\chi \rightarrow \nu\bar{\nu}$), etc.



Bustamante & Connolly, PRL 122, 041101 (2019)
arXiv 1711.11043

Why Study UHE Neutrinos?

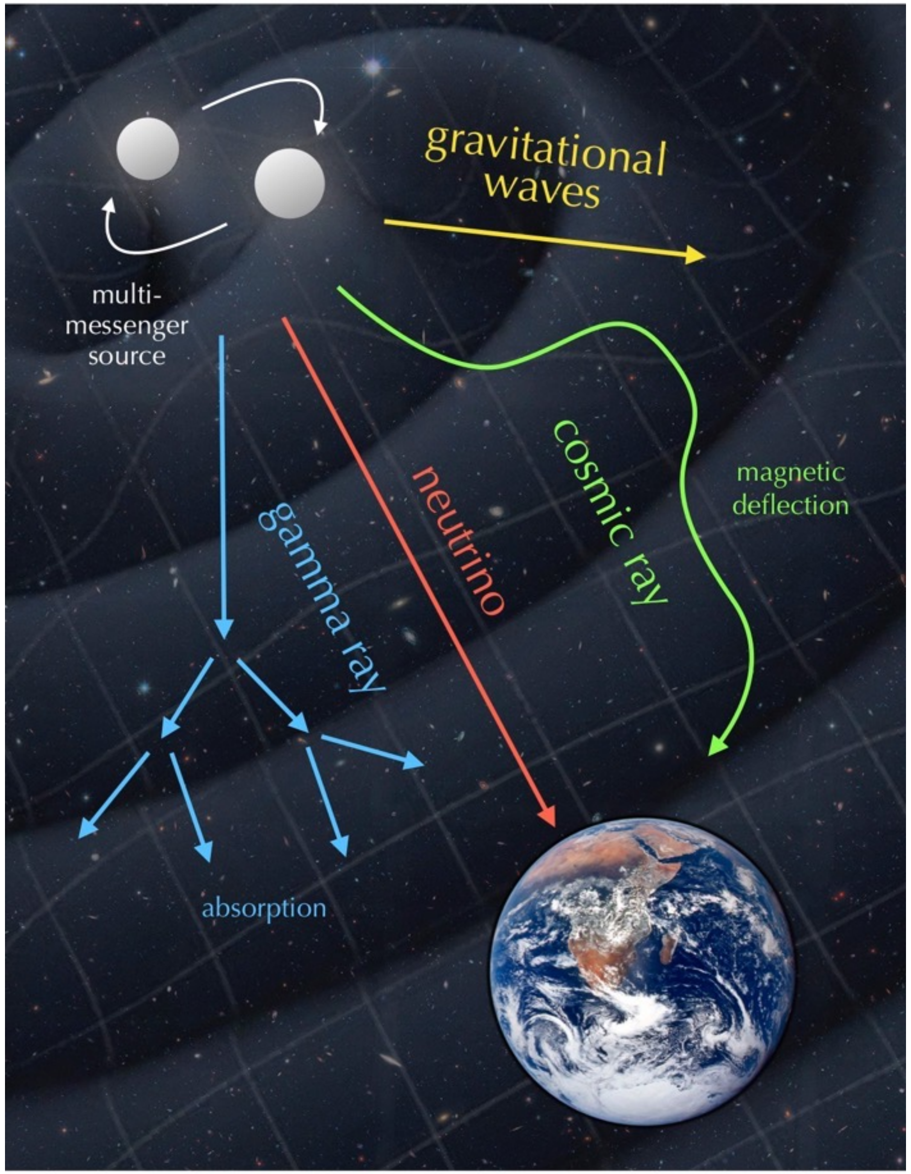
Origin of UHE cosmic rays – where and how?

Multimessenger astronomy

Neutrinos are unique probes of the distant, high-energy universe

- γ-rays absorbed
- CRs deflected; absorbed after ~100 Mpc

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p(n) + \pi^{0}(\pi^{+})$$



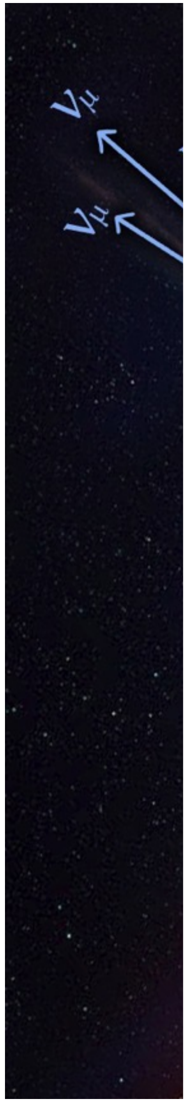
Astrophysical Neutrinos

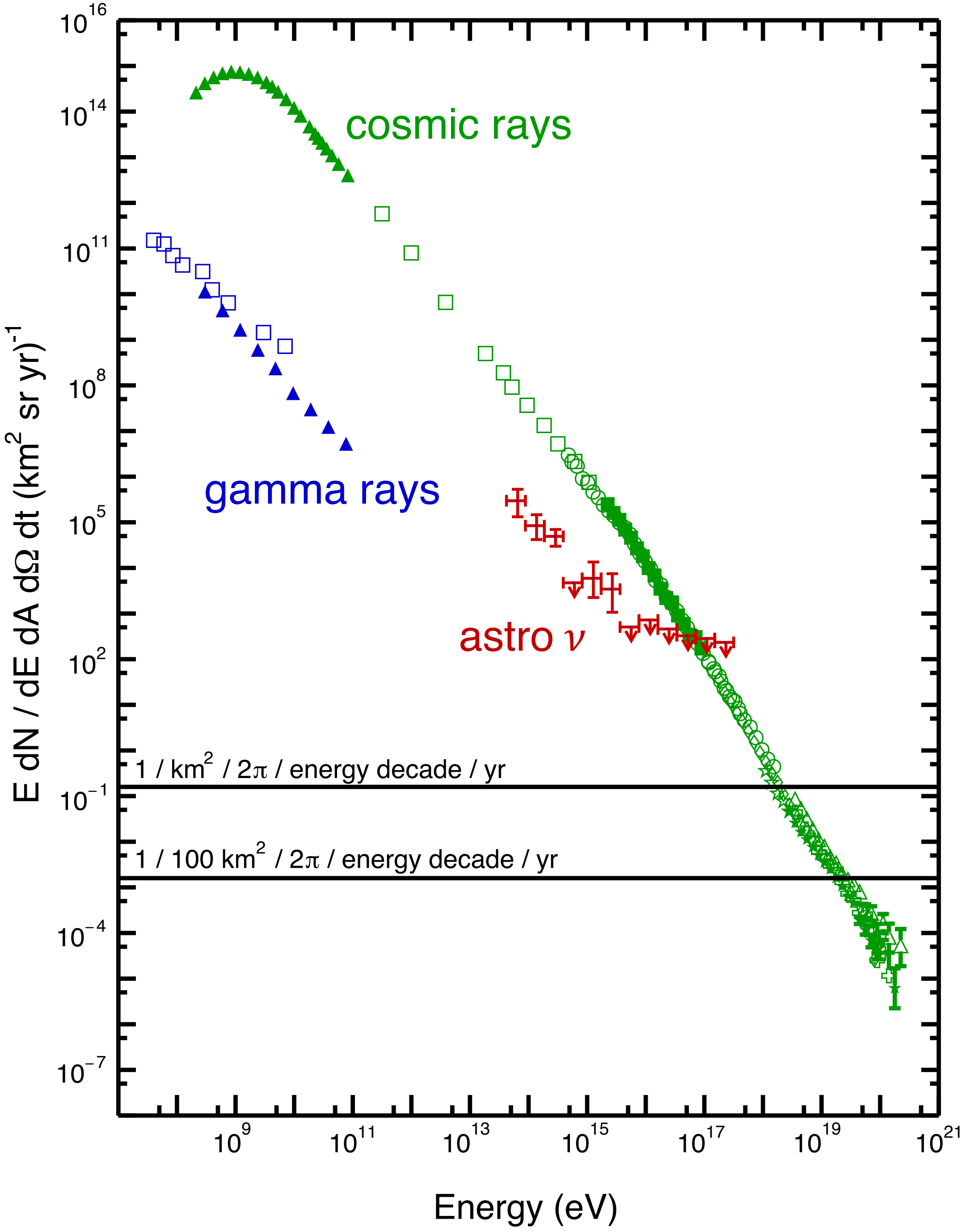
Neutrinos born in (or near) the cosmic ray accelerators

Unambiguous proof of hadronic acceleration

Detected in 2013!

(Only hints of sources)





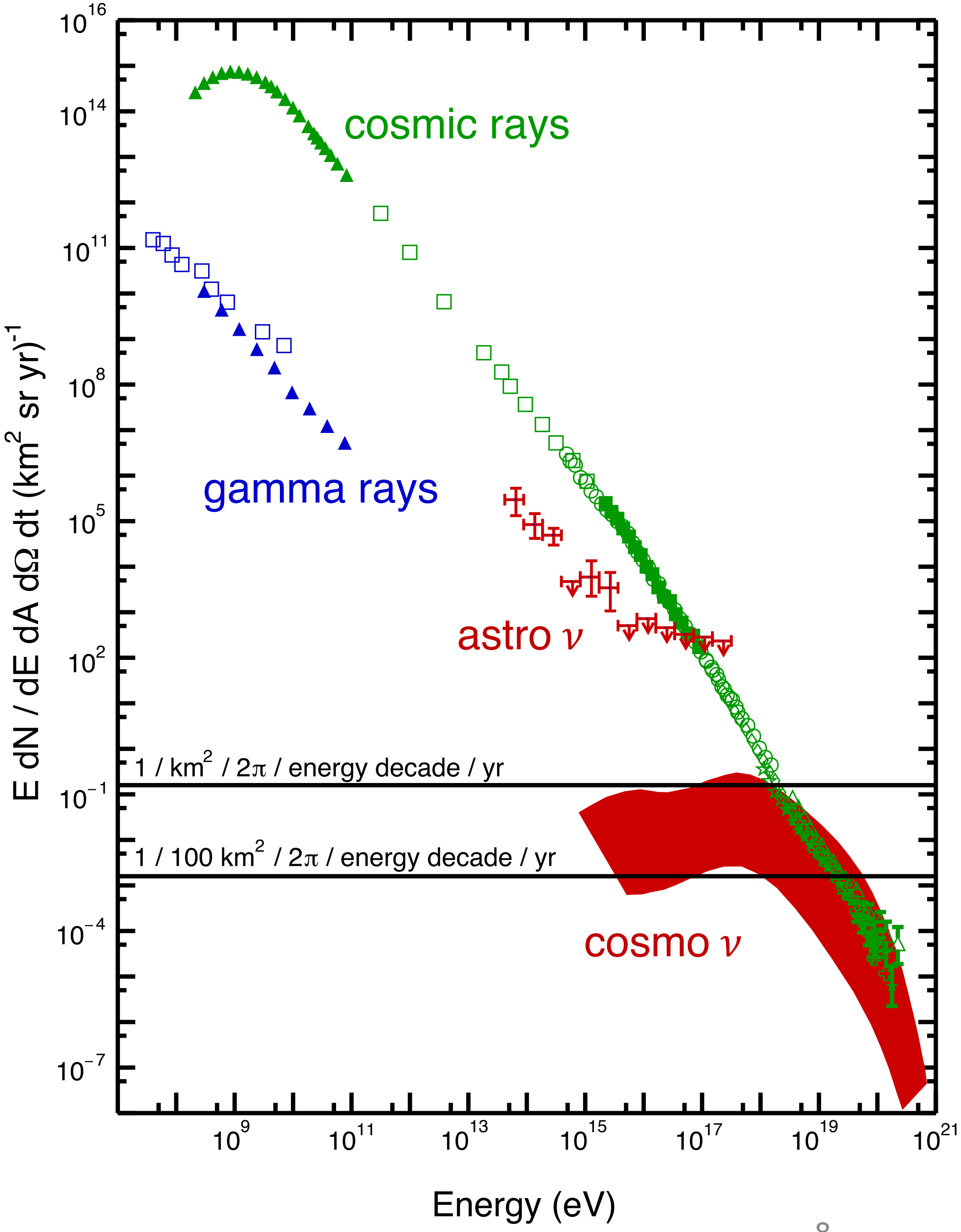
Cosmogenic Neutrinos

Pions from the GZK interaction further decay

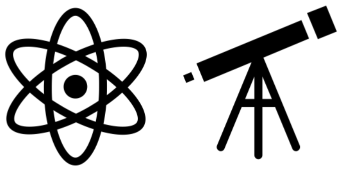
$$p + \gamma \rightarrow n + \pi^+$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Undetected. But! Shape encodes important astrophysics:

- Maximum accelerating energy
- Source redshift evolution
- Cosmic ray composition



Bottom Line Up Front



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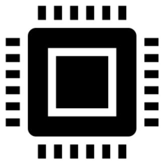

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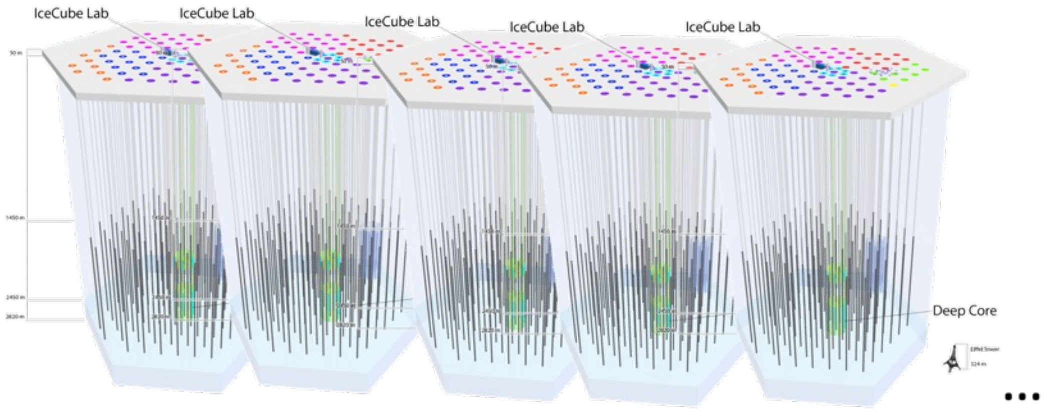
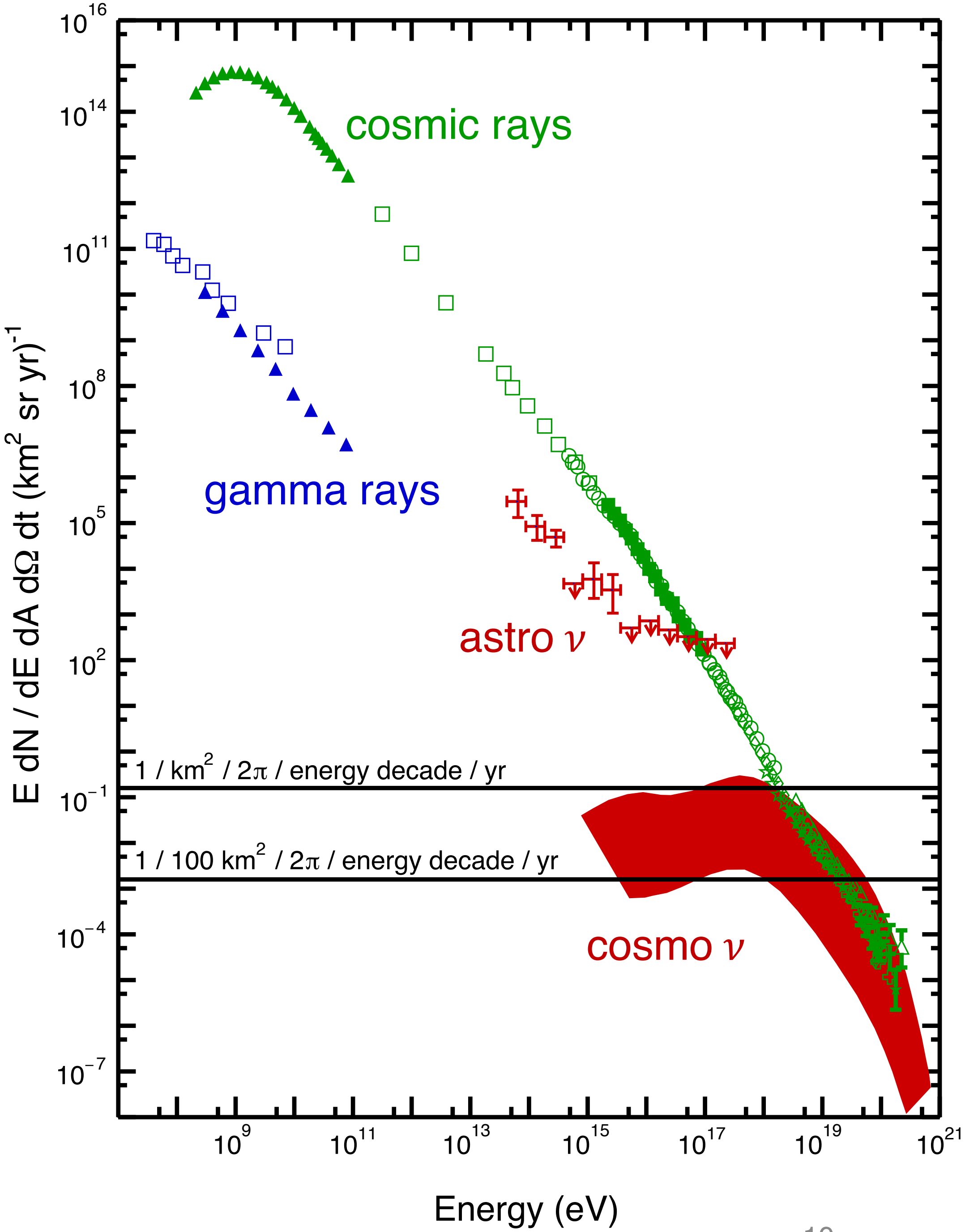
Observational challenges

UHE neutrinos are rare: ≪ 1 /km³/yr

Fluxes too small for optical Cherenkov technology that underpins Baikal, ANTARES, IceCube, KM3NET, etc.



Need a new approach…



Radio Cherenkov Effect

“Askaryan” Emission

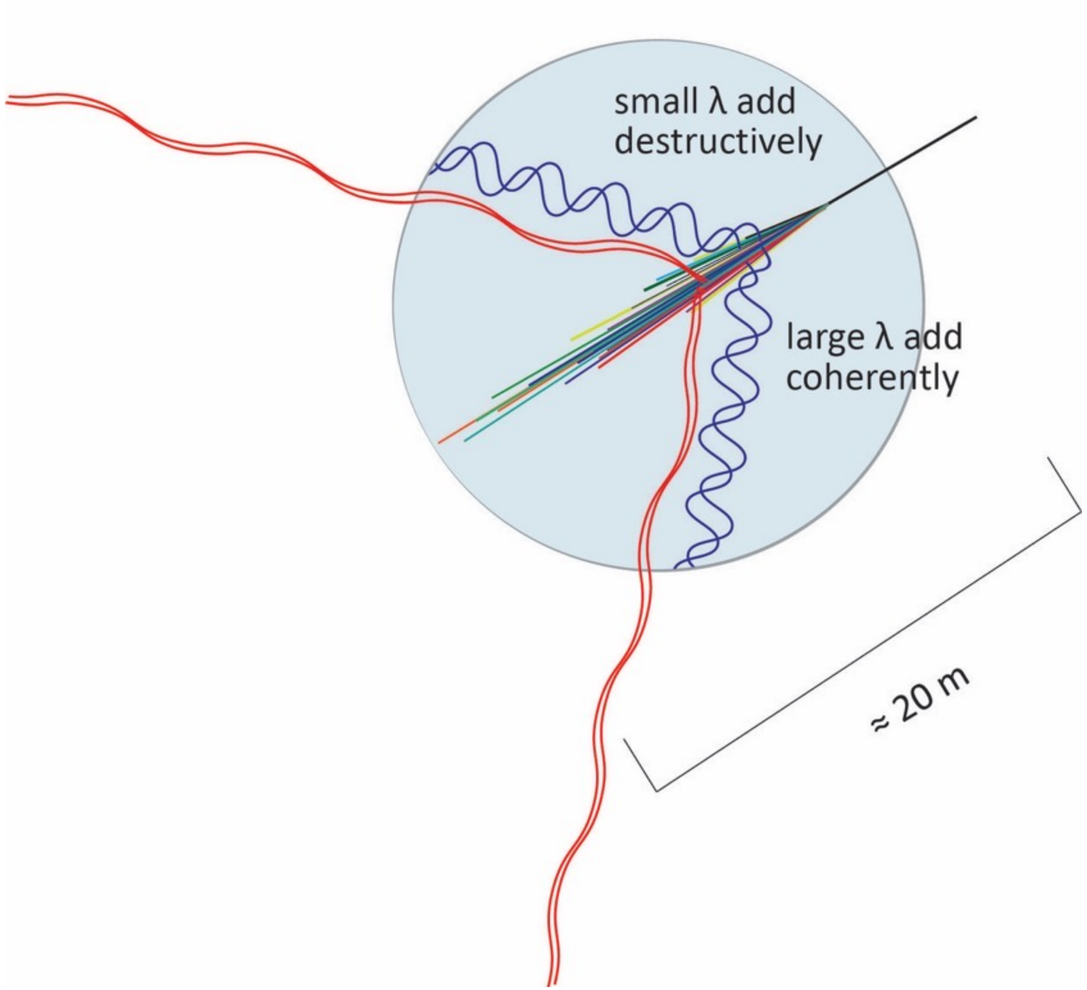
Suggested by G. Askaryan in 1962

Neutrino-induced particle shower becomes net *negatively* charged

Wavelengths the size of the shower add *coherently*

10cm transverse size →

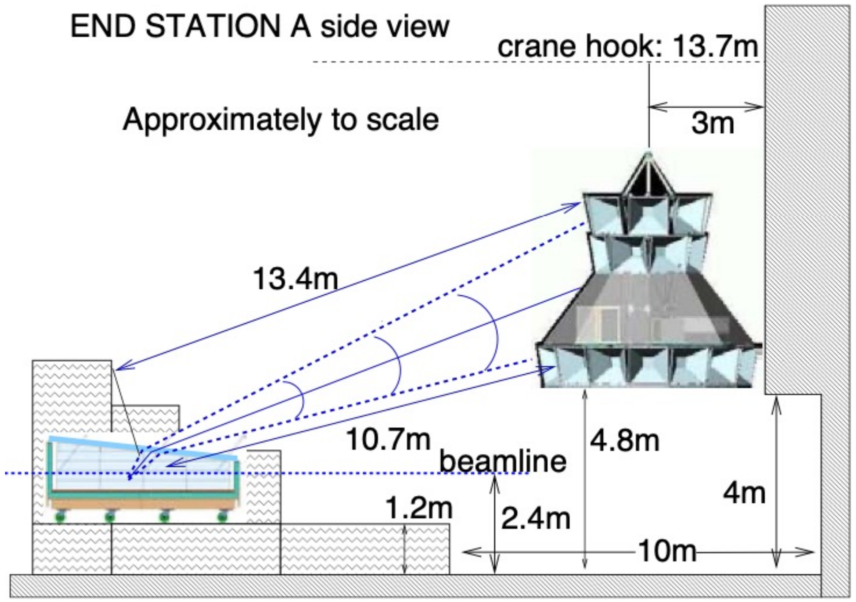
$\mathcal{O}$(MHz)- $\mathcal{O}$(1GHz) broadband radio pulse

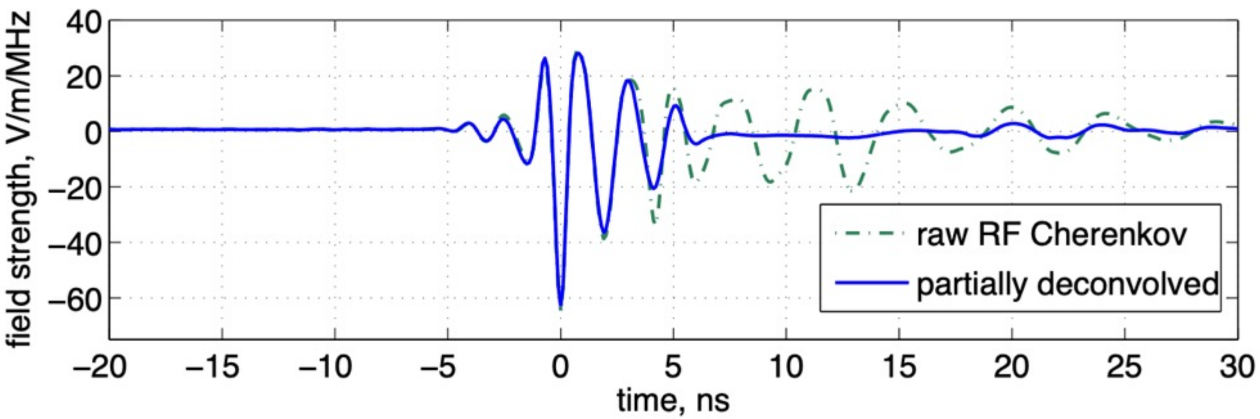


First Observation in Ice

Observed in ice by the ANITA collaboration in 2007 at SLAC End Station A (T486 experiment)

Observed a fast, polarized pulse whose power scaled with shower energy squared (coherent!)



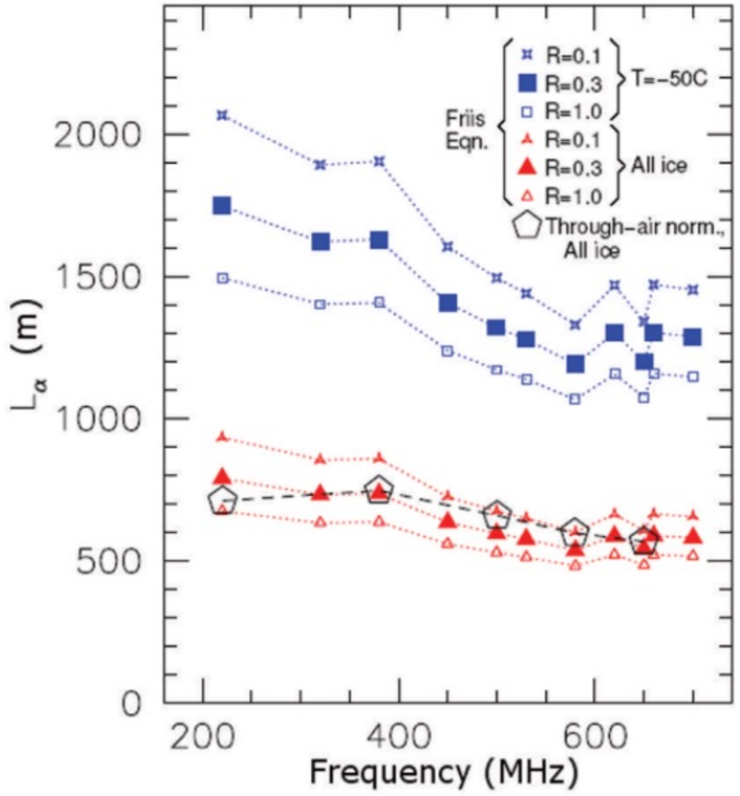


ANITA PRL 99, 171101 (2007)

Polar Ice

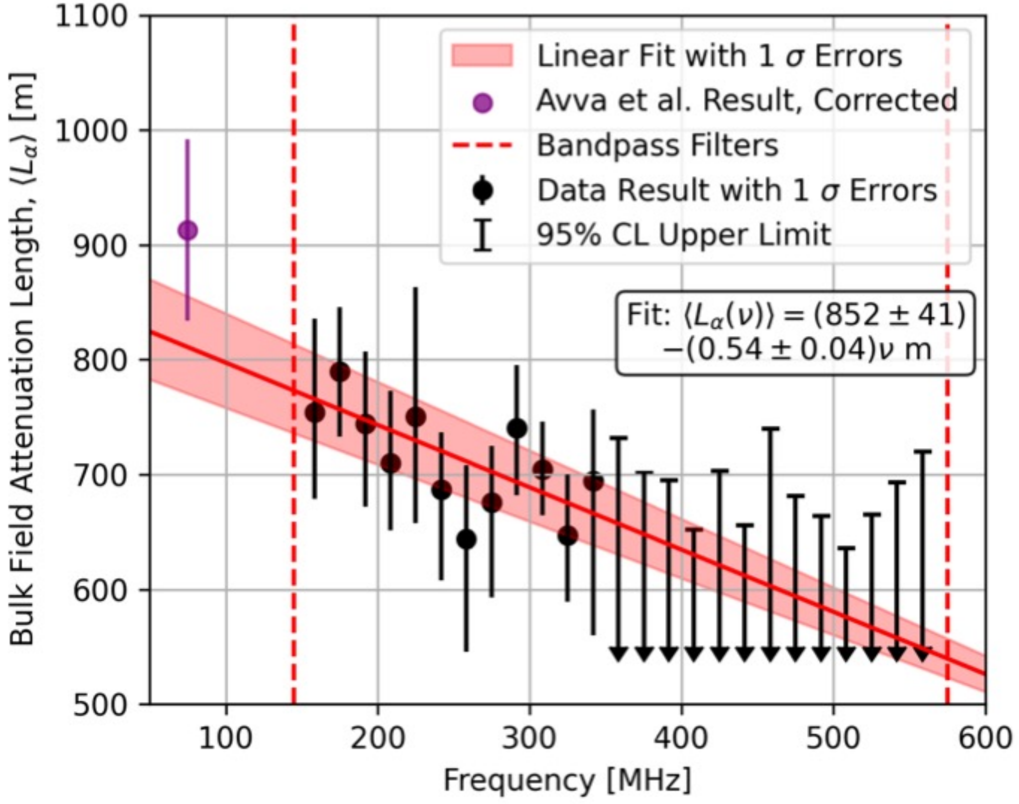
Polar ice has $O(1km)$ attenuation lengths at radio frequencies; ideal for a sparse detector of adequate size

South Pole



Barwick *et al*, JGlac V51 I173, 2005

Summit Station, Greenland



RNO-G Collab, arXiv 2201.07846

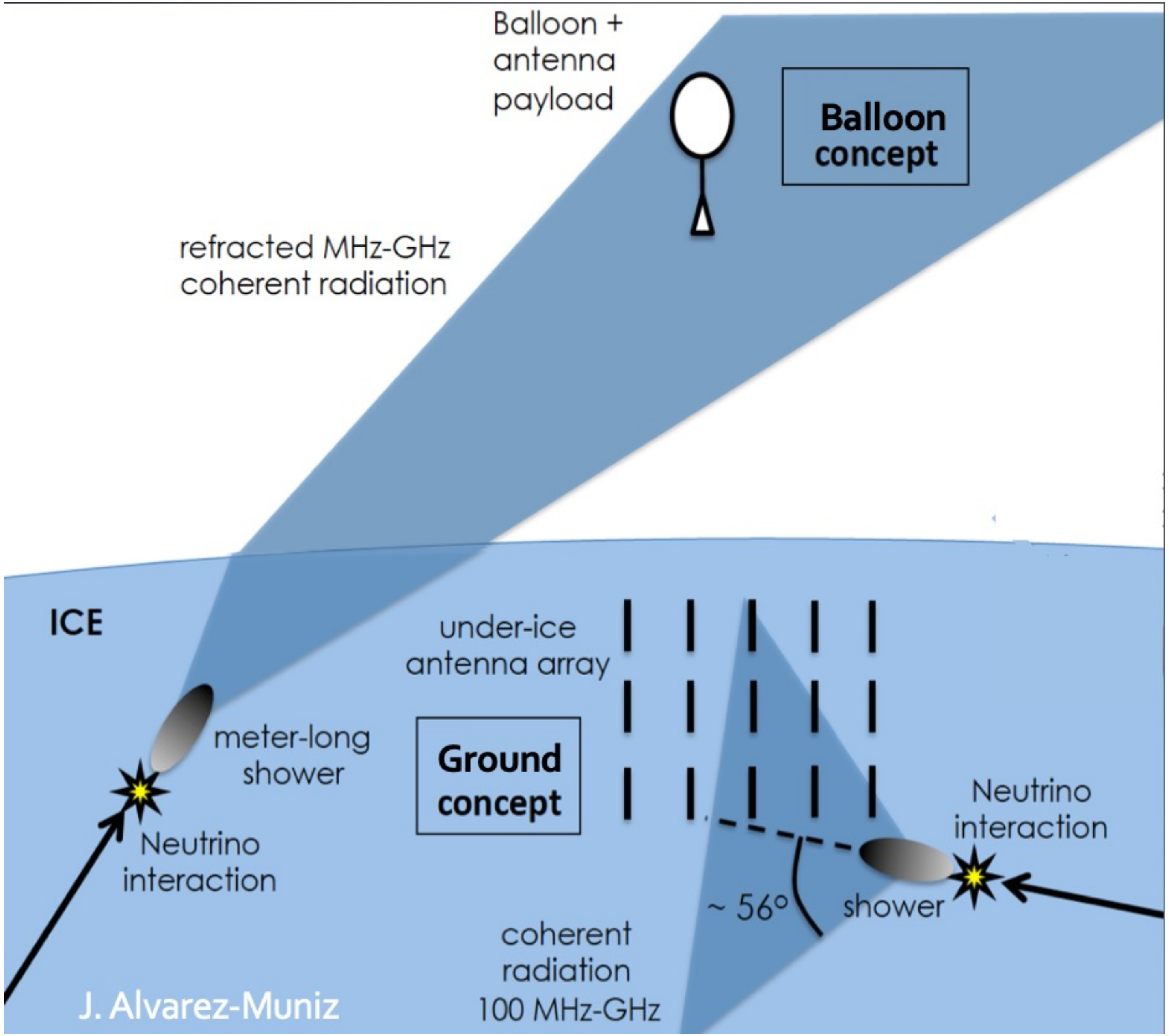
Two basic strategies to view the emission:

- Panoptically, with remote observatories
- *in-situ*, with embedded arrays

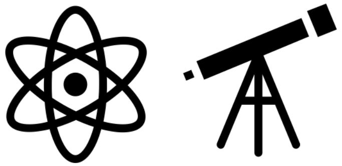
Complimentary approaches!

Panoptic observatories have larger apertures, but higher energy thresholds

Disclaimer: I'm only addressing "passive" probes, *in ice*.



Bottom Line Up Front



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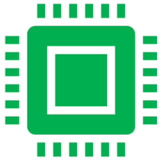
The radio technique offers an efficient way to achieve necessary effective volumes (>100 km^3)



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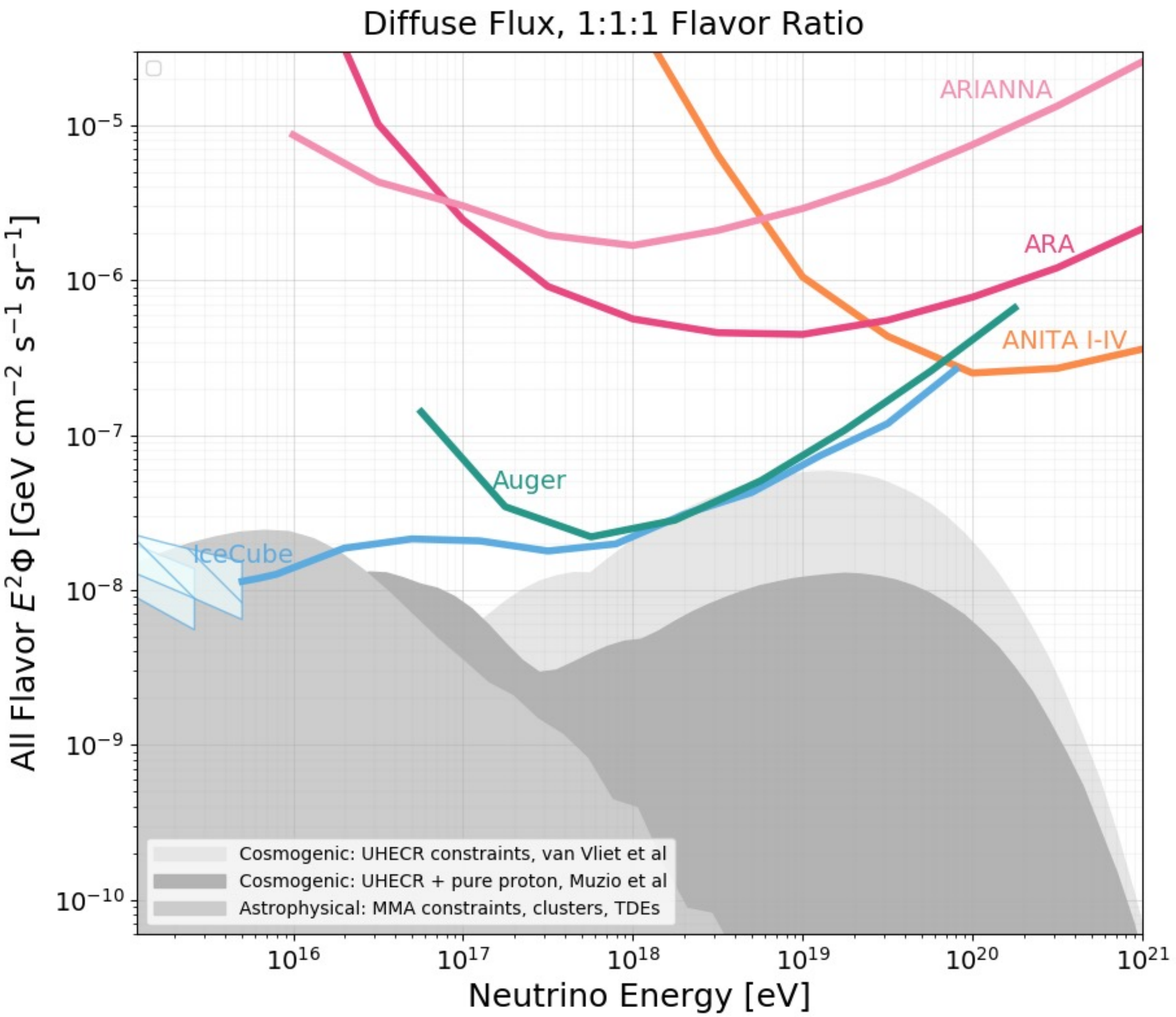
Status Quo

Series of experiments have demonstrated the feasibility and scalability of the radio technology



ANITA

Antarctic Impulsive Transient Antenna

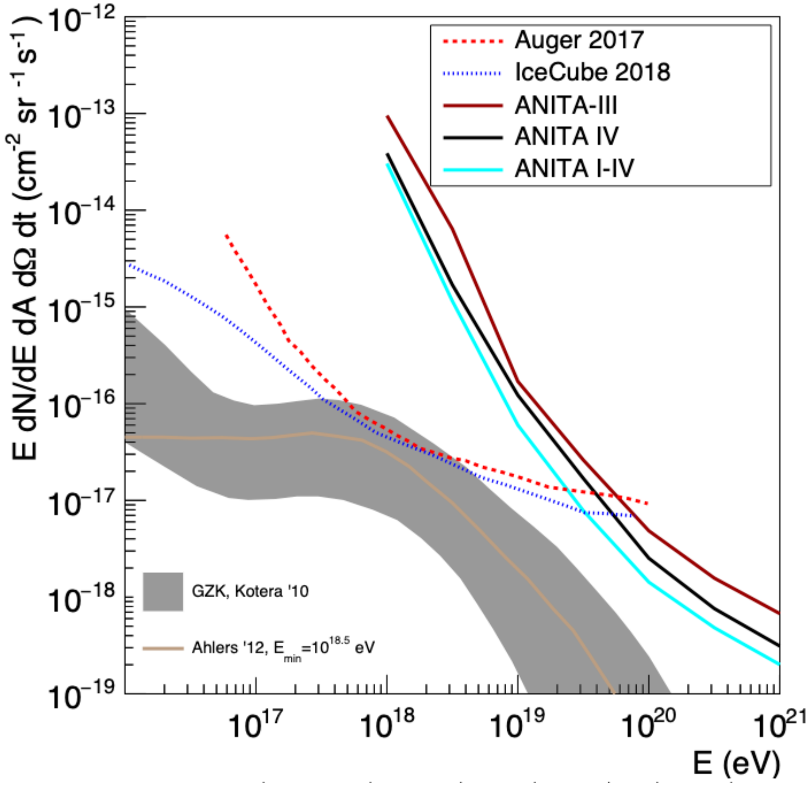
Array of horn antennas suspended from NASA Long Duration Balloon (LDB)

Four flights 2006-2016

- Askaryan (neutrino) channel: no excess above background
- ~100 UHECR seen

World leading limit above $10^{19.5}$ eV

Demonstrates the feasibility of the panoptic method

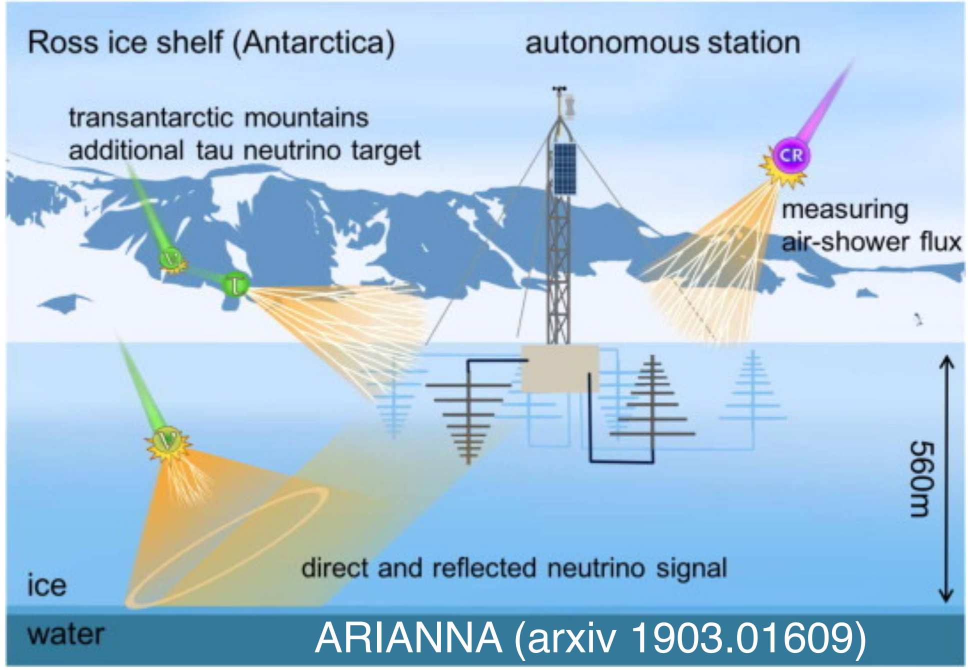


ANITA, PRD 99, 122001 (2019)
arXiv 1902.04005

ARIANNA

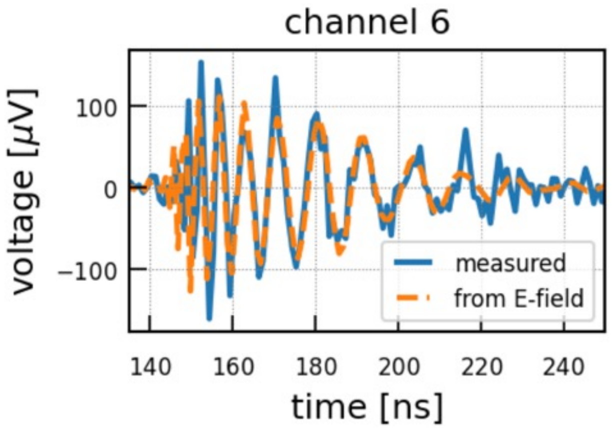
Antarctic Ross Ice-Shelf Neutrino Array

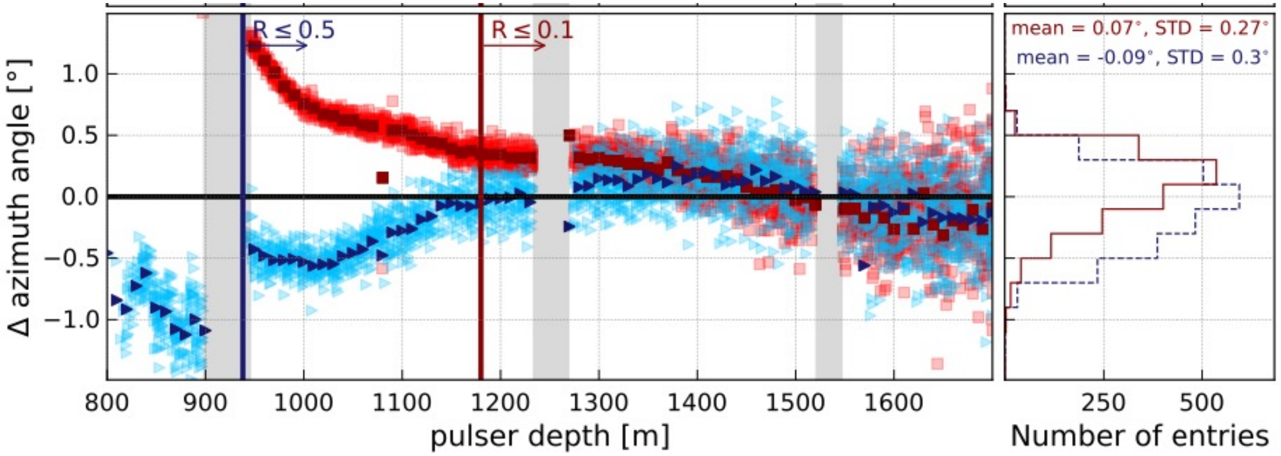
Array of LPDA antennas deployed near ice surface at Moore's Bay in Antarctica



Ran 2011-2020, demonstrated feasibility and performance of autonomous, shallow detector

- Cosmic rays ~1/day (calibration beam)





ARIANNA, JINST 15 (2020) P09039

- RF signal direction to ~0.3°

ARA

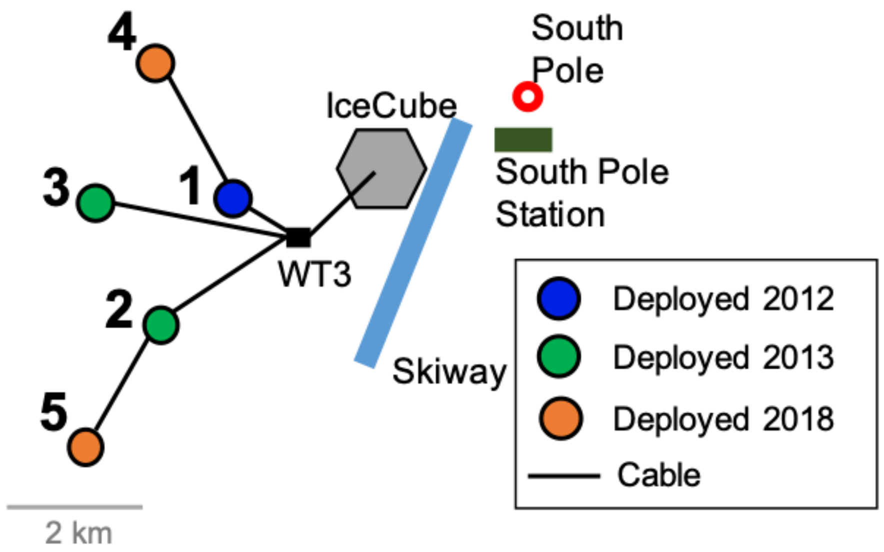
Askaryan Radio Array

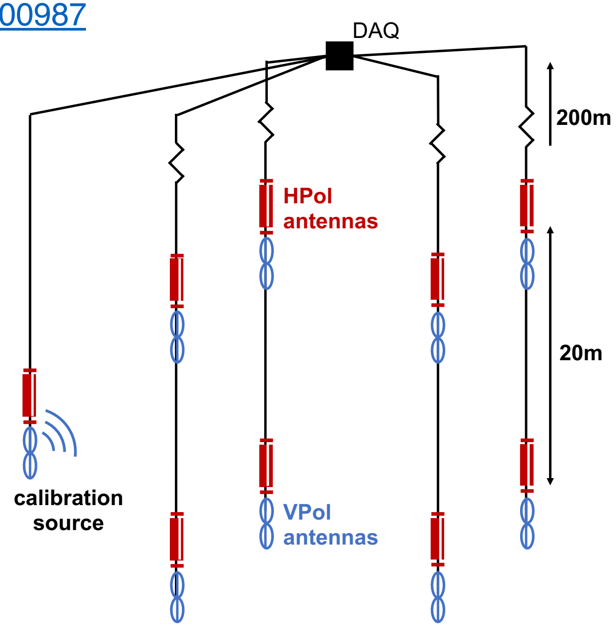
Array of 5 stations, deployed 2012-2018 (still running) at South Pole

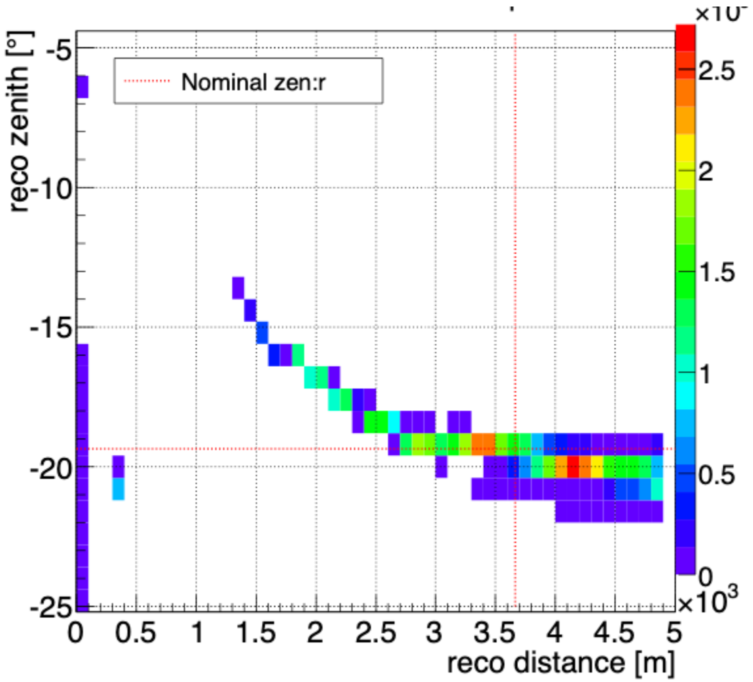
Demonstrated feasibility and performance of deep detector

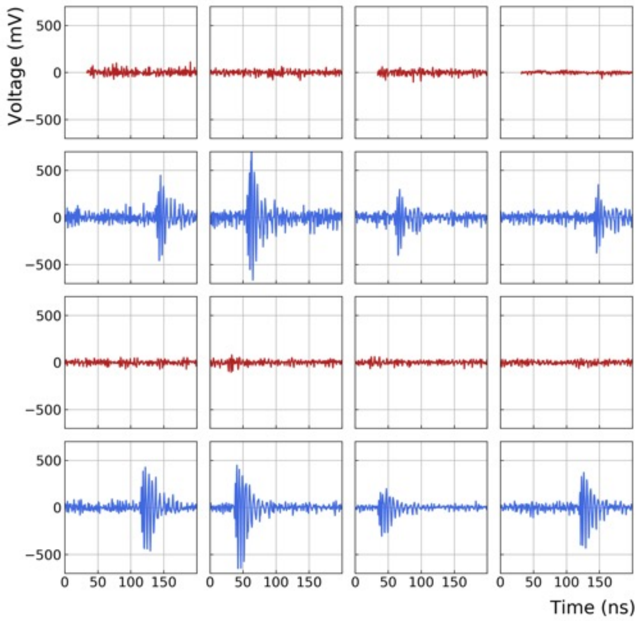
- Ex: Reco vertex direction and distance to ~1° and ~30%

ARA, PRD 102 4 043021 (2020), arXiv 1912.00987







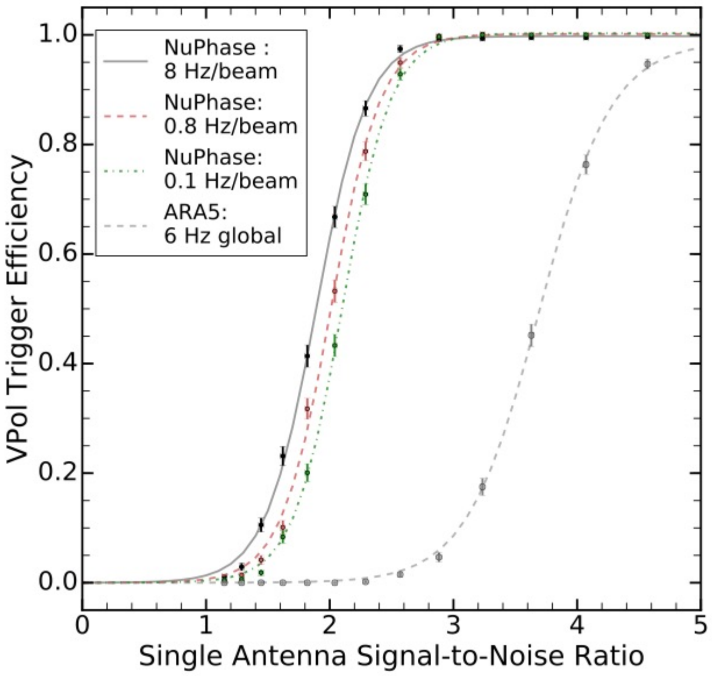


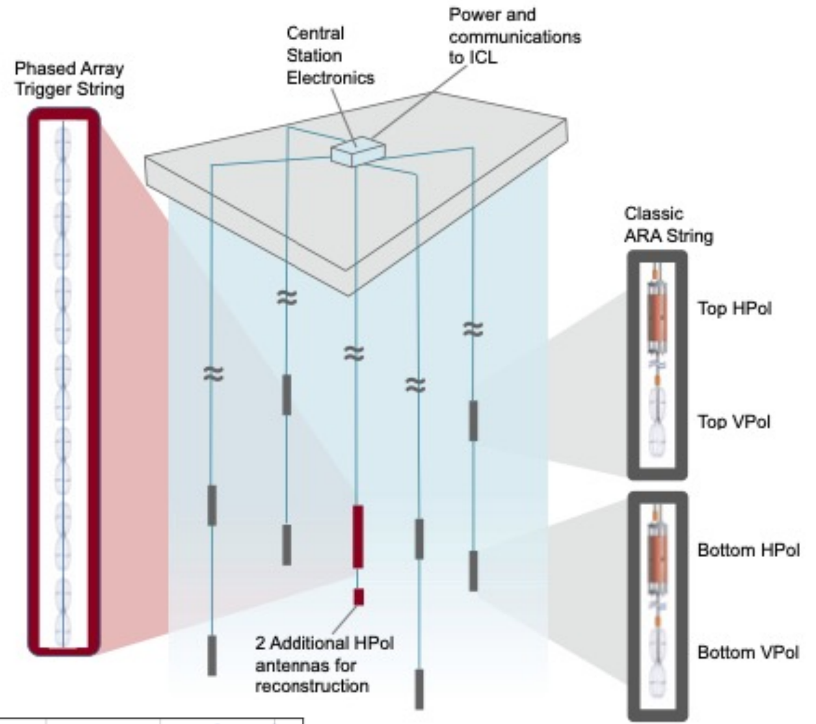
ARA, Astropart Phys 2019.01.004 arXiv 1712.03301

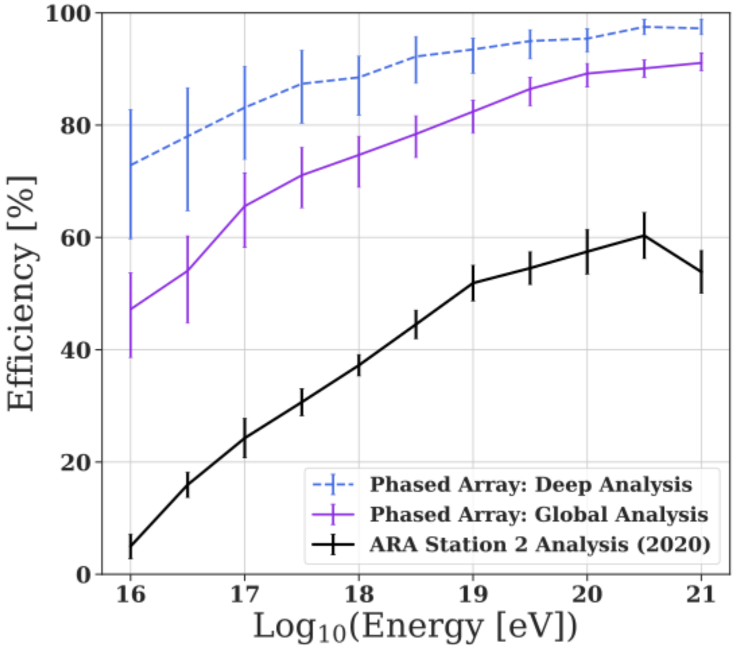
ARA Phased Array

Latest ARA station has threshold-lowering phased array trigger – 2x more effective volume at trigger level at 10 PeV!

ARA, NimA 2019.01.067, arXiv 1809.04573



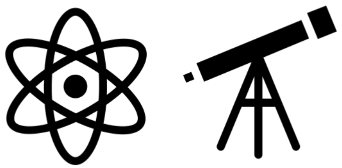




ARA, PRD 105 122006 (2022) arXiv 2202.07080

And events *can* be analyzed

Bottom Line Up Front



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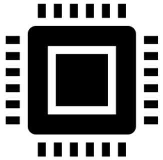

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PUEO

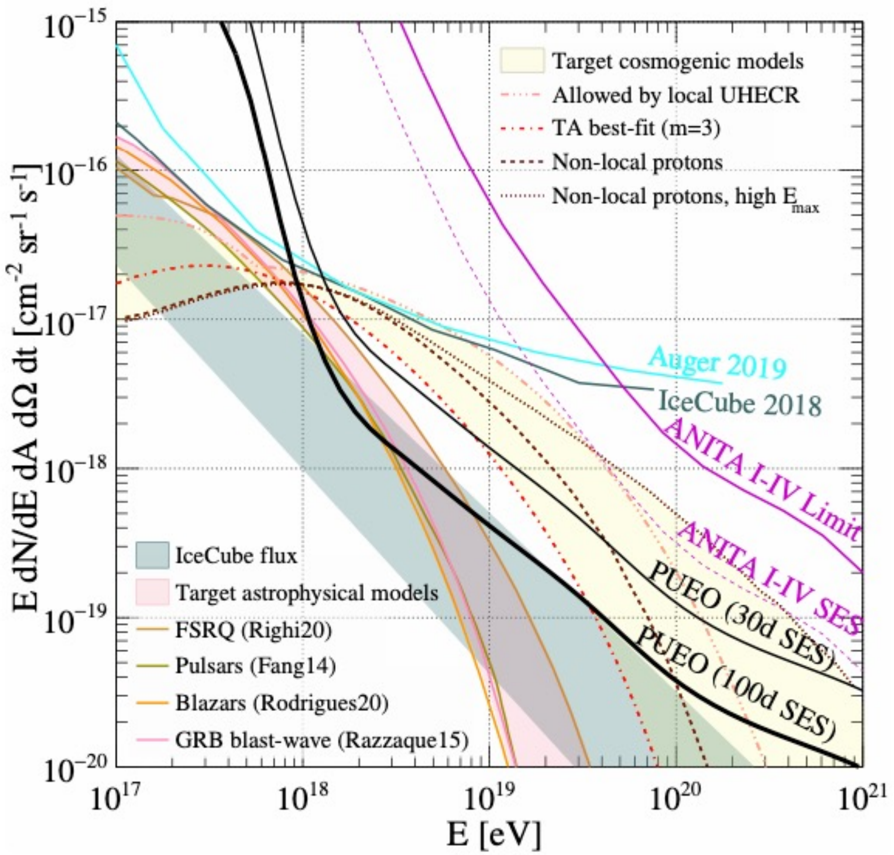
Payload for Ultra High Energy Observations

Successor to ANITA experiment—array of horns, with phased trigger, to fly on an LDB

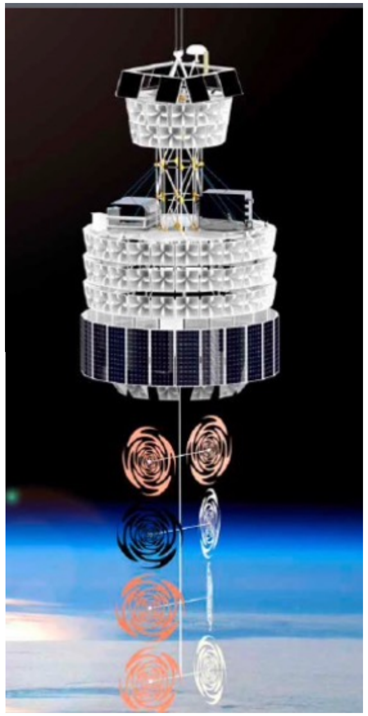
>10x more sensitive than ANITA

Large instantaneous volume for transients, point sources, MMA

Funded through the NASA Pioneer Program, flight in ~2024!



JINST 16 (2021) 08, P08035
arXiv 2010.02892

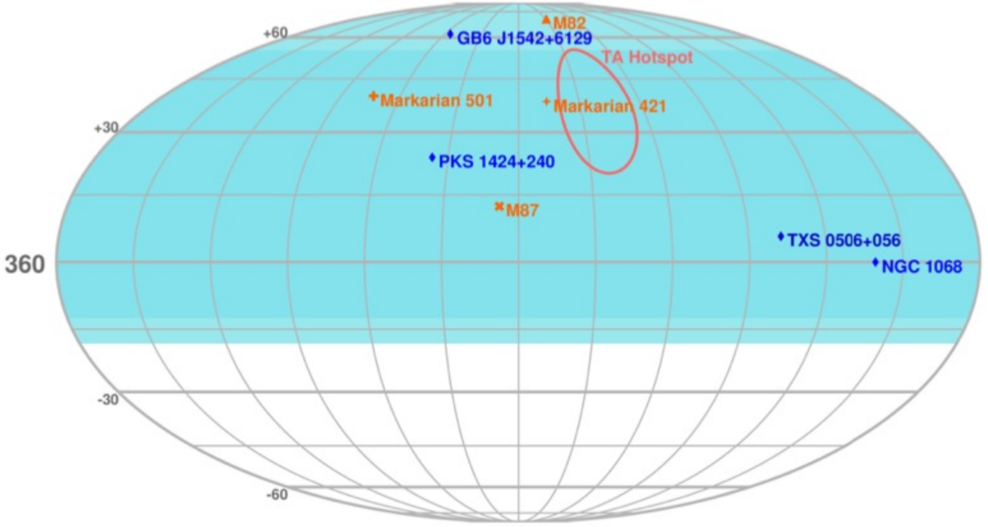


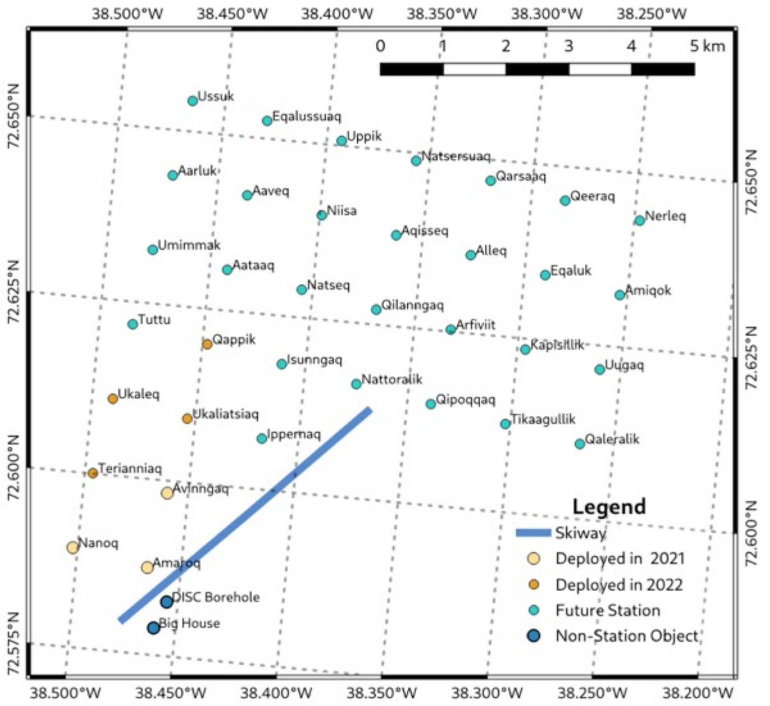
RNO-G

Radio Neutrino Observatory – Greenland

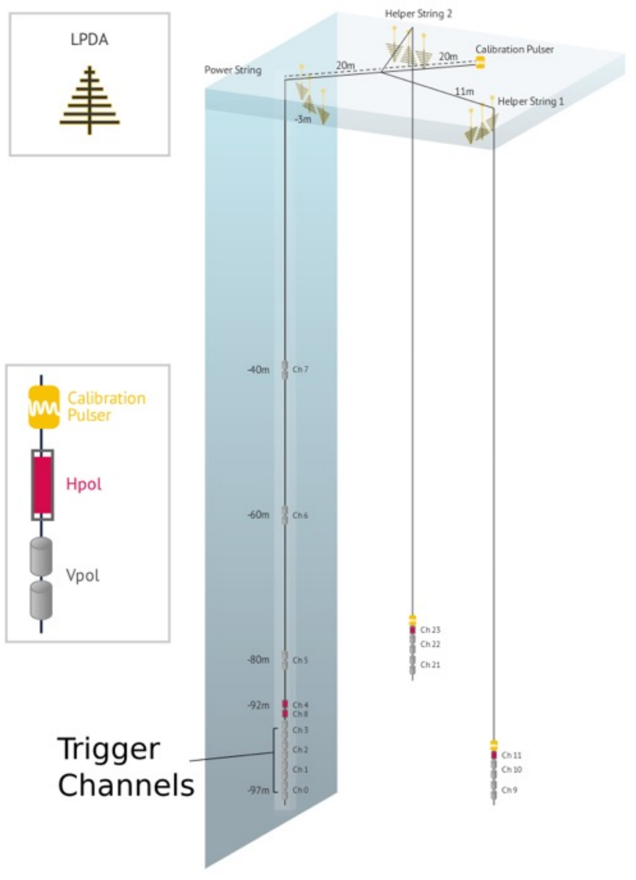
Deployment under way in Greenland since 2021, goal of 35 stations

First UHE observatory in the northern hemisphere





RNO-G, JINST 16 P03025 (2021)
[arXiv 2010.2279](https://arxiv.org/abs/2010.2279)



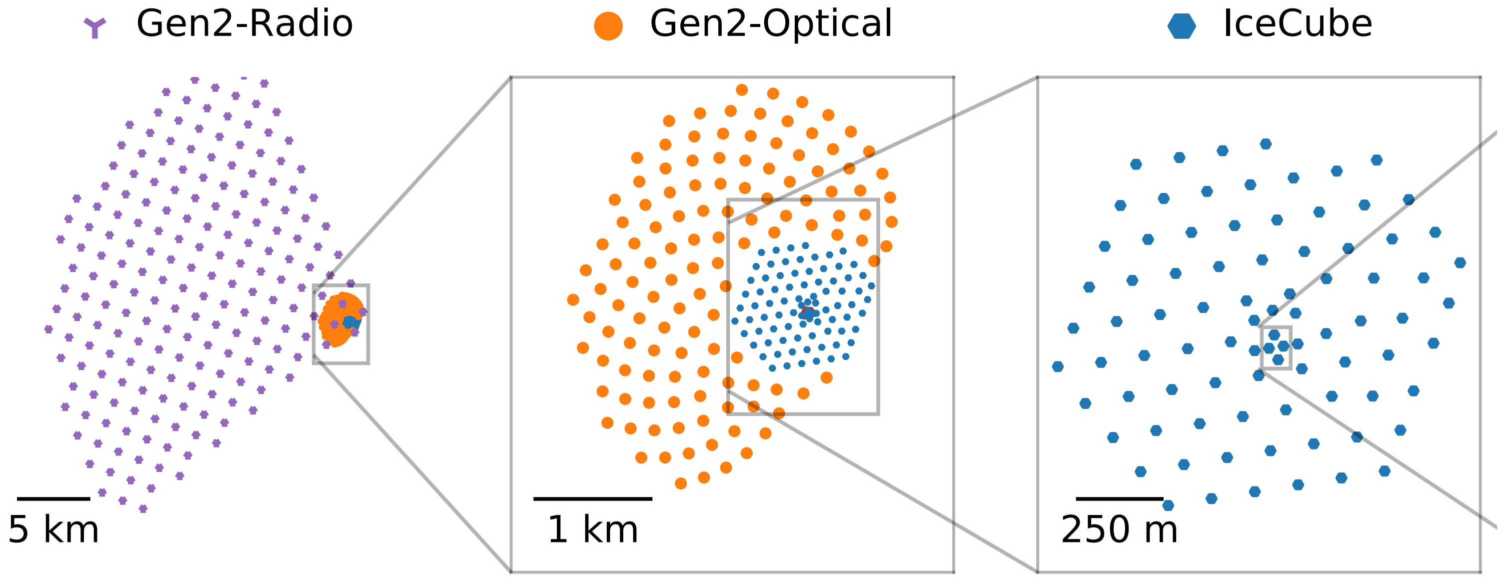
Combines strength of deep (ARA, RICE) and shallow (ARIANNA) technology

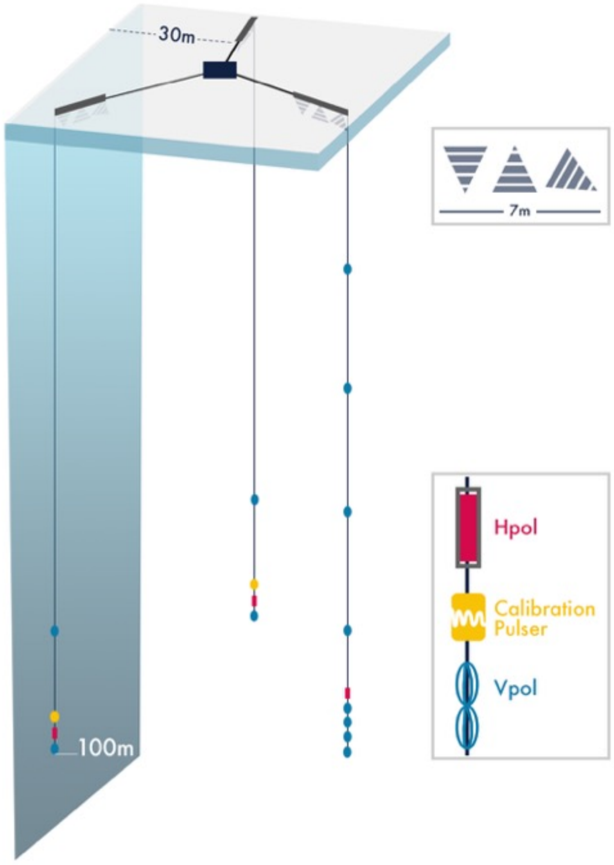
IceCube-Gen2 Radio

One element of the IceCube-Gen2 Facility

~200 station over 500 km^2, again comibining the deep and shallow technology

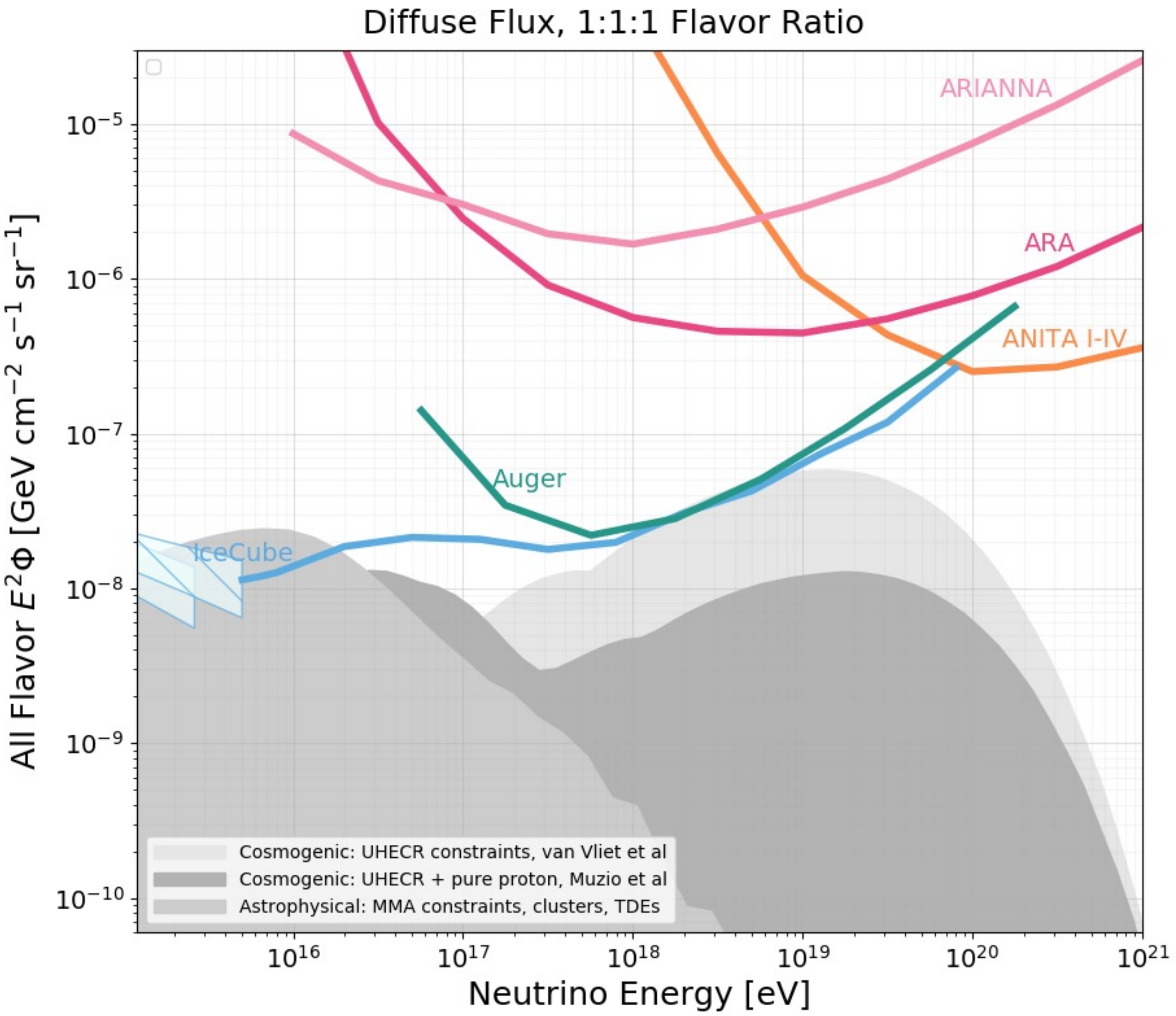
IceCube-Gen2, J. Phys. G 6 060501 (2021)





Experimental Outlook

Goal is sensitivity (90% CL UL) below 10^{-9} at 1 EeV



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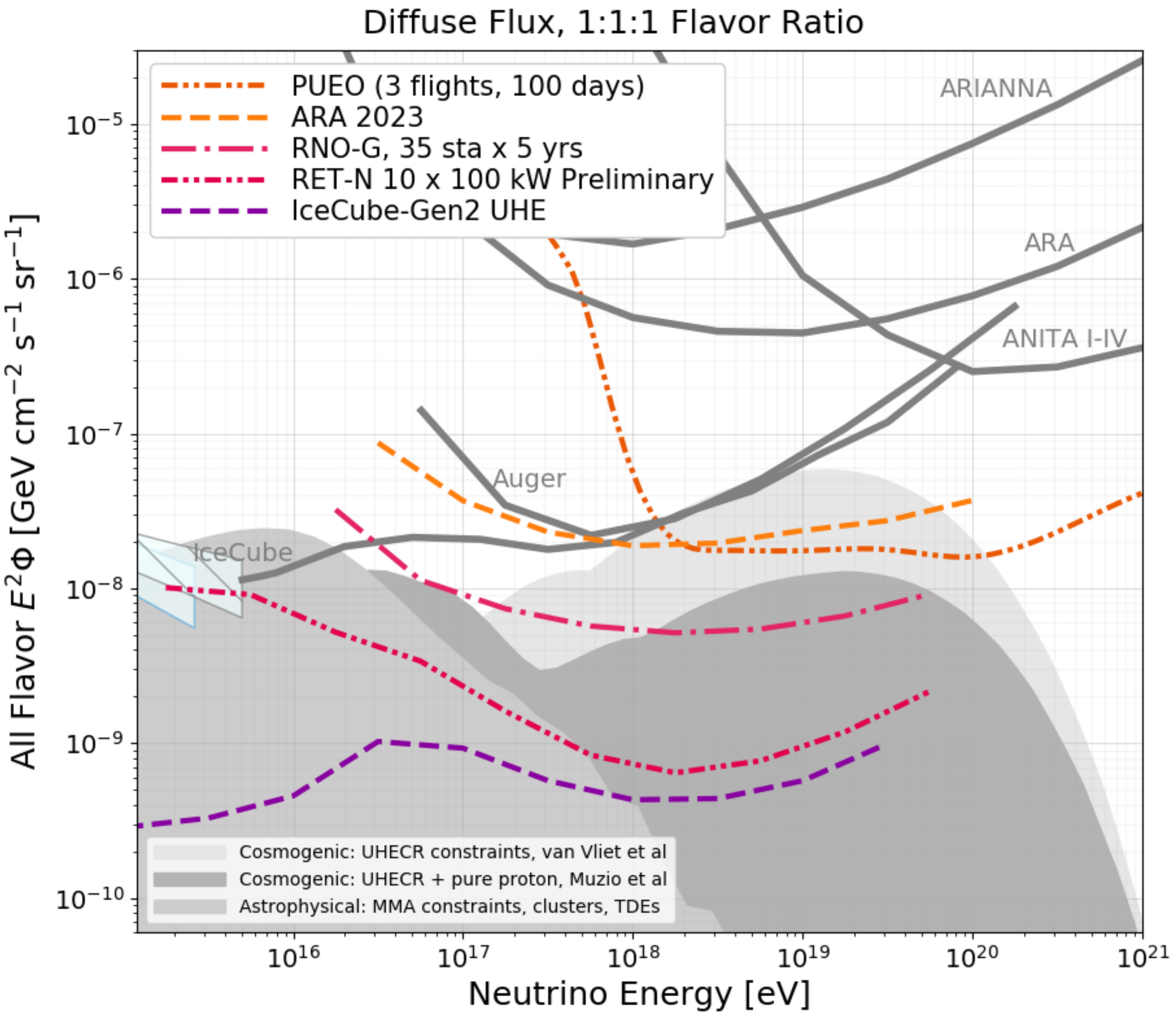
Future experiments chart steady progress in opening this discovery space



Ongoing Work

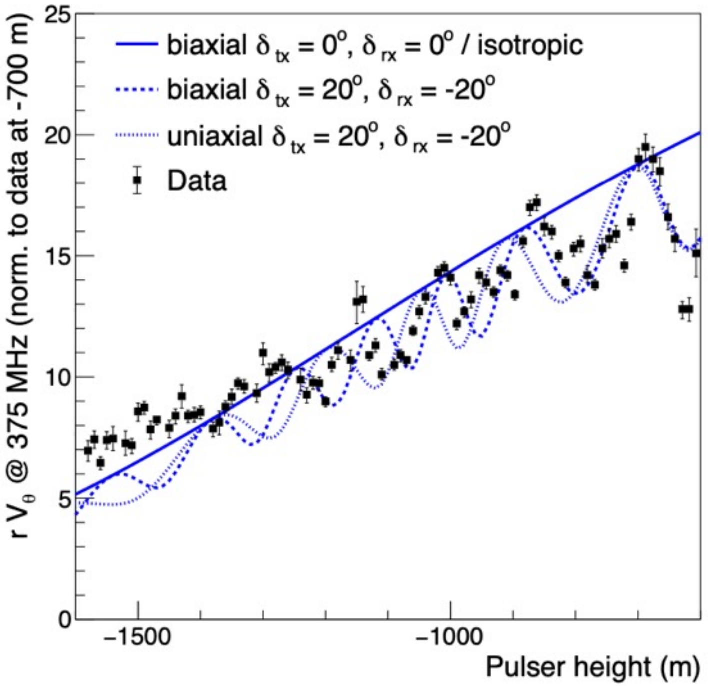
A Small Sampling…

Understanding the ice–horizontal propagation, birefringence

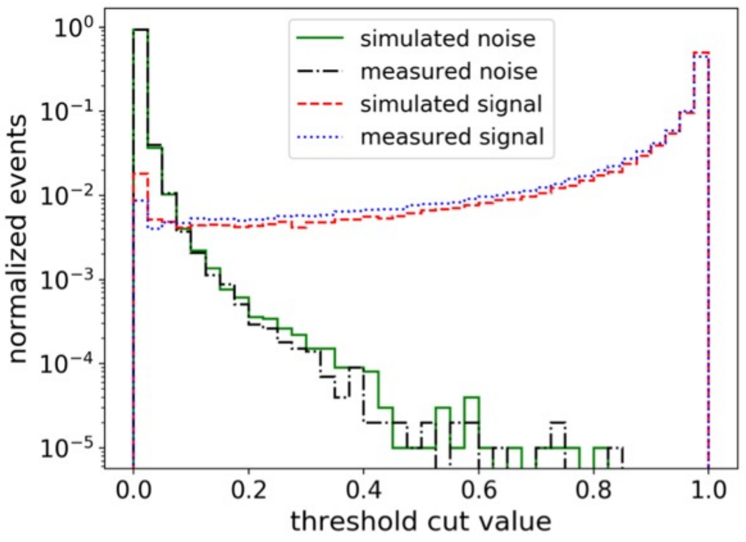
Quantifying and rejecting backgrounds– anthropogenic, cosmic rays/muons

Algorithmic—triggering, reconstruction of energy, direction, flavor

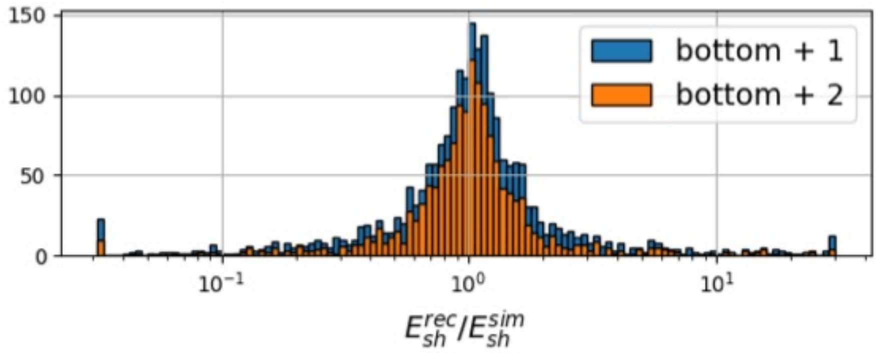
Connolly et al, PRD 105 123012 (2022)
Birefringence explains features in ARA data



ARIANNA ICRC 2021
Machine Learning (CNN) trigger



RNO-G, EPJC 82: 147 (2022)
"Forward Folding" energy reconstruction has ~30% uncertainty on shower energy



Conclusions

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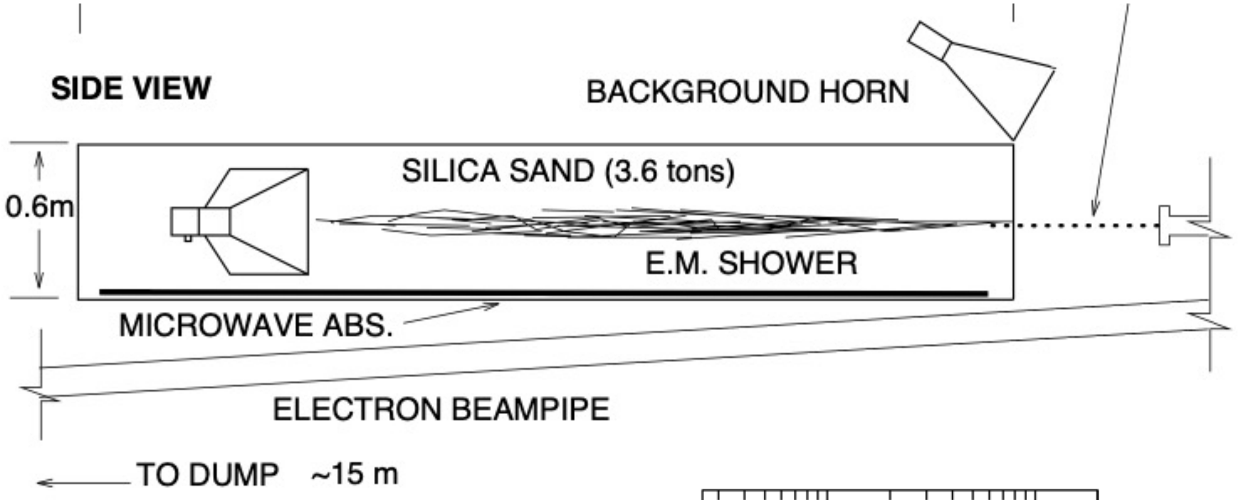
The presenter thanks the NSF through Award 1903885.

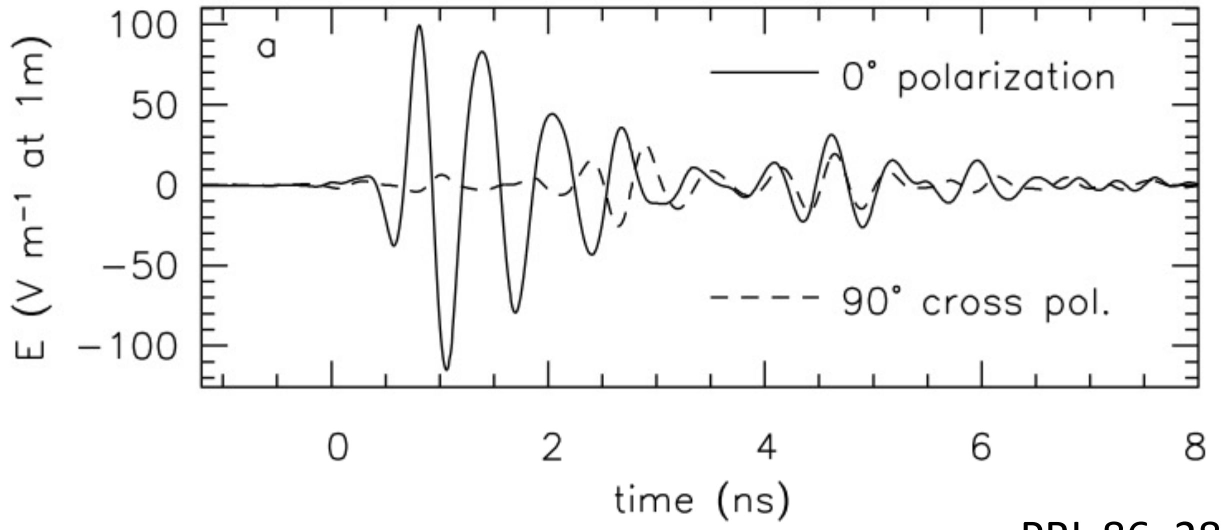
Backup

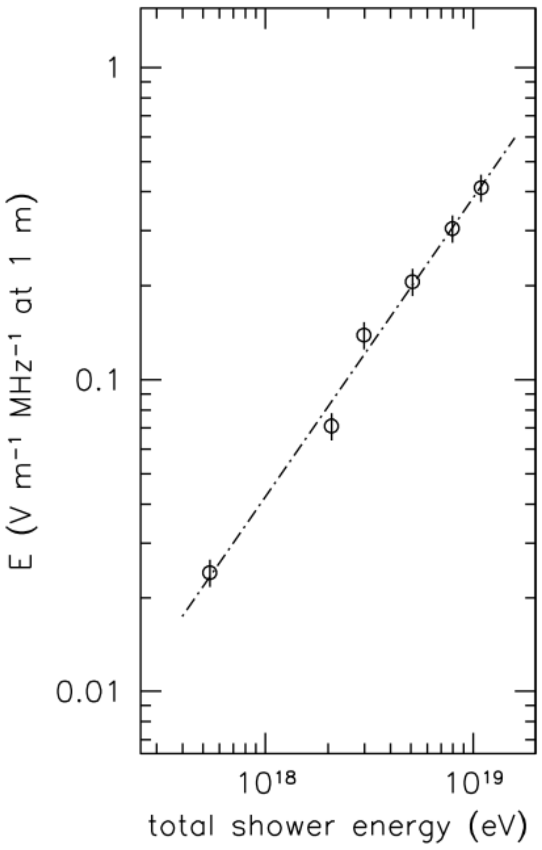
First Observation

First observed at SLAC Final Focus Test Beam in 2000 on sand

Observed a fast, 100% polarized pulse whose power scaled with shower energy (coherent!)







PRL 86, 2802 (2001)

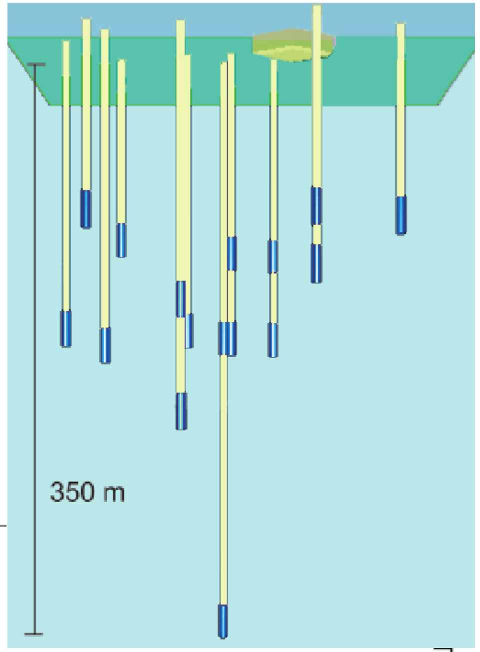
RICE

Radio Ice Cherenkov Experiment

Array of antennas deployed opportunistically with AMANDA

Located at the South Pole, ran 2000-2010

Demonstrated the feasibility of the *in-situ* approach



PRD 85, 062004 (2012)